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The influence of microstructural characteristics on the mechanical properties of Ti6Al4V alloy produced by the powder metallurgy technique

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Abstract: The influence of hot-pressing (HP-ing) parameters on the microstructure, tensile properties and impact toughness of Ti6Al4V alloy produced by the powder metallurgy (PM) technique was evaluated. The experimental results show that variations in the microstructural morphology and residual porosity play an important role in affecting the mechanical properties of this alloy. The lamellar microstructure with a higher density, obtained by HP-ing above the β-transition temperature (T_{β}), was found to exibit a higher tensile strenght and toughness than the globular microstructure produced below T_{β}. Although both types of microstructure show a mixed fracture, the ductile mode was more pronounced in the case of the fully lamellar microstructure. By controlling the HP-ing pressure and duration time, the globular microstructure, with lower porosity, improved tensile strength and ductility in combination with a better resistance to crack initation and propagation, can be obtained.

Keywords: powder metallurgy, hot pressing, tensile properties, toughness, microstructural morphology, porosity.

INTRODUCTION

The demand for the use of titanium and its alloys in many areas of civil (automotive, chemical, food and oil industry) and military applications has increased over the past years, not only by the necesssity for weight reductions, but mainly owing to the extraordinary properties of these materials. On the other side, titanium, with its excellent biocompatibility, mechanical and elecrochemical properties, has been well recognized as the most promising biomaterial in surgery and density prosthesis and implants. One of the most widely used titanium alloys is certainly the Ti6Al4V alloy. Because of the excellent combination of strength, toughness and corrosion resistance, this alloy is widely applied in many areas, such as pressure vessels, aircraft-turbine and compressor blades and disscs, surgical implants, *etc.*[1–5]

In order to apply Ti6Al4V alloy parts for all these purposes, the material must have a high strength to density ratio and high fracture toughness. However, in

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many cases these requirements cannot be attained due to the high porosity and disadvantageous microstructures which, produced by different processing techniques, may have a detrimental influence on the properties. In contrast to this, alloys produced by the powder metallurgy (PM) technique are characterized by lower residual porosity and fine grain size, which improve the strength and toughness. The percent of residual porosity, as well as a wide range of microstructural parameters, including prior β grain size, colony size, thickness of grain boundary α phase, α lamellar spacing and interface morphology, can be controlled by various thermo-mechanical treatments.[6] Since a specific porosity/microstructural morphology combination is believed to provide satisfactory strength and toughness, it is of a great interest to study the dependence of mechanical properties on microstructural features determined by individual processing parameters.[7–9]

In this study, Ti6Al4V alloy produced *via* the PM technique was subjected to various hot-pressing (HP-ing) conditions in order to induce a variety of microstructures. This, in turn, was followed by investigating the resulting tensile and impact toughness properties as a functon of the selected HP-ing parameters.

EXPERIMENTAL

The initial material employed in this study was a pre-alloyed Ti6Al4V powder, recived from the Leybold-Heraeus Company, produced by a rotating electrode process (REP). Powder particles with a mean size of 150 μm (according to the specifications of the manufacturer) were consolidated by vacuum HP-ing at 950 ºC, below the β-transition temperature (T_β), and at 1100 °C (above T_β) for 60 and 120 min under pressure of 40 and 60 MPa.

The microstructures were examined using a "Reichert" light optical microscope (LOM), whereas the densities of the compacts were determined in xylene applying the Archimedes method. The total and open porosity were also estimated by the same method.

The tensile properties were determined in air at room temperature using a universal "Instron 8033" testing machine with a displacement rate of 0.2 mm/min. Three cylindrical specimens of 8 mm diameter and 20 mm gauge length were used for each tensile test.

Instrumented impact test were conducted at room temperature using a 350 J "Tinius Olsen" machine. The toughnesss was determined using at least three non-standard 7x7x5.5 mm U-notched Charpy specimens, with a 1.5 mm deep notch and 1 mm root radius. For the examinations, a pendulum blow speed of 5.11 m/s was employed.

In order to gain an insight into the mechanism of fracture, a fractographic investigation using a "JEOL JSM-35" scanning electron microscope (SEM) was performed on broken test specimens.

RESULTS AND DISCUSSION

Typical microstructures obtained during the HP-ing process are illustrated in Fig. 1. It can be seen that relatively small variations in the processing parameters resulted in considerable variations in the microstructural morphology. The HP-ing conducted below T_β yielded a globular microstructure (Figs. 1a–c), while at the HP-ing temperature above T_β, a fully lamellar microstructure was formed (Figs. 1d–f).

Coarser globular microstructures were produced with increasing HP-ing pressure and time. Lon-term HP-ing yielded significantly coarser α grain size (Figs. 1a

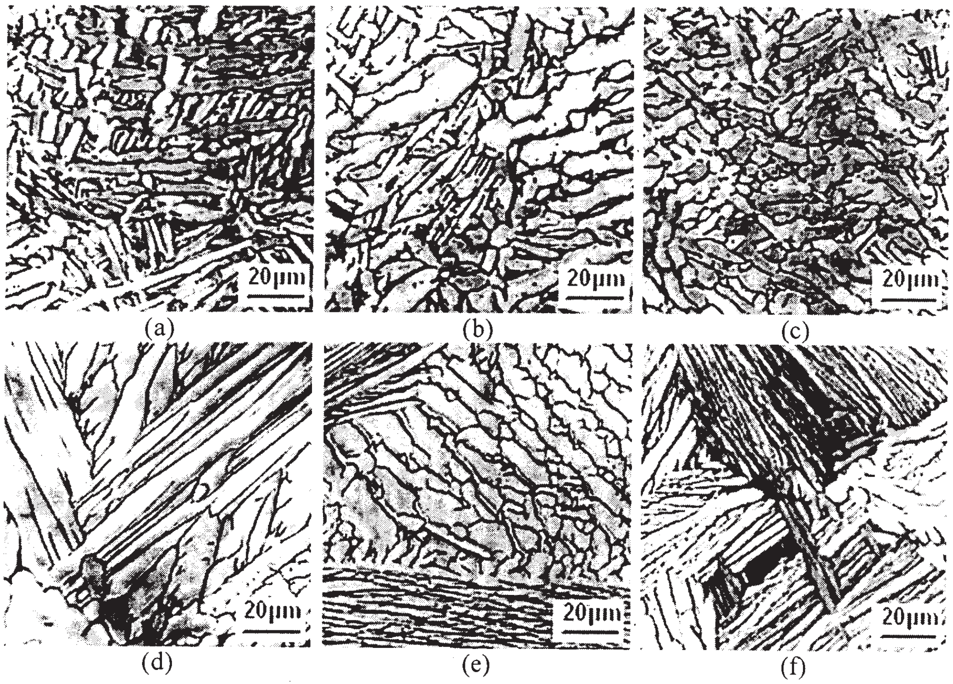

Fig. 1. LOM Micrographs showing the microsructure of the PM-Ti6Al4V alloy hot-pressed at: (a) 950 °C and 40 MPa for 60 min, (b) 950 °C and 40 MPa for 120 min, (c) 950 °C and 60 MPa for 120 min, (d) 1100 °C and 40 MPa for 60 min, (e) 1100 °C and 40 MPa for 120 min and (f) 1100 °C and 60 MPa for 120 min.

and b). However, the processing pressure had a quite different influence on the grain growth. Namely, the higher pressure appeared to retard the growth of the α phase during HP-ing in the (α + β) phase region. Thus, the microstructure of the specimen HP-ed for 120 min under a pressure of 40 MPa exhibited much coarser grains than the specimen exposed for the same time to a pressure of 60 MPa (Figs. 1b and c). In contrast, HP-ing for 120 min at 1100 °C refined both the colony size and the α lamellae. As shown in Figs. 1d and e, long HP-ing just above T_β produced slightly thinner α lamellae. The processing pressure of 60 MPa had a similar effect on the colony size and lamellar spacing. Both were successfully refined further. While the degree of refinement in the colony size was not large, it was most likely greater in the α lamellae. Increasing the HP-ing pressure significantly refined the α lamellae and made the microstructure of the PM Ti6Al4V alloy more uniform, Fig. 1f. This particular effect is interpreted as the HP-ing pressure increased the α lamellae nucleation rate and retarded the growth of these lamellae, resulting in a rafined lamellar microstructure.

On the other hand, the various microstructures displey differences in the residual porosity. The alloy density and the estimated percentage of total and open porosity are presented in Table I.

TABLE I. Density and porosity of the PM-Ti6Al4V alloy as a function of the hot-pressing parameters

Specimen	Temperature/°C	Time/min	Pressure MPa	Density g cm^{-3}	Closed porosity/%	Open porosity/%	Total porosity/%
1	950	60	40	4.30	3.10	0.71	3.81
2	950	120	40	4.35	2.28	0.19	2.47
3	950	60	60	4.36	2.22	0.02	2.24
4	950	120	60	4.37	1.94	0.08	2.02
5	1100	60	40	4.39	1.53	0.04	1.57
6	1100	120	40	4.39	1.54	0.03	1.57
7	1100	60	60	4.39	1.56	0.01	1.57
8	1100	120	60	4.39	1.56	0.01	1.57

The specimens HP-ed in the β phase region showed less total porosity and were more dense than the specimens consolidated in the (α+β) region. The presence of pores, acting as crack initiators, has a significant influence on the tensile characteristics and toughness of the compacts.[10] As can be seen from Table II, the fully lamellar microstructures with some porosity are characterized by a higher tensile strength and a higher impact toughness when compared to the globular microstructures with a high amount of residual porosity. Due to the high concentration of stress generated around the pores, cracks are formed more easily and a lower energy is required for fracture. Therefore, fracture of the fully dense specimens HP-ed at 1100 °C occured at higher applied loads. Some improvements in the yield and tensile strength were obtained by increasing the exposure time and/or applied pressure. The beneficial effects of these parameters are correlated with lower porosity, particularly open porosity. However, the nature and wake of the crack parth suggest that microstructural parameters, such as morphology and the α grain size, also have a significant influence on the fracture resistance of this alloy. The overal path of a crack in a specimin with a lamellar microstructure is rather tortuous, indicating that its fracture resistance is improved in relation to one with a globular microstructure, not only because of its lower porosity, but also because of crack deflection and branching. Since the microcracks initiate and propagate along the lamellar interfaces, the main crack can be stopped or deflected by a barrier represented by grains with a lamellar interface orientation diverged from the direction of the crack propagation. Fully lamellar microstructures possessing the same percentage of porosity display significantly higher strengths than globular microstructures. It should be noted, however, that the strength of globular microstructures is mainly dependant on amount of porosity.

Refinement of the lamellar dimensions did not induce a large increase in the strength. The values of the tensile strength of coarse lamellar microstructures were only slightly lower than those of fine lamellar microstructures. At the same time, the coarse lamellar microstructures also showed a slightly higher tensile elongation relative to that of the fine lamellar microstructures (compare specimens 5 and 6 with 7 and 8, Table II). In spite of the expectation that the globular microstructures would exhibit higher elongation, the results of this study verified that there was no significant difference in the tensile elongation between lamellar and globular microstructures, due to the higher residual porosity in the latter microstructures. On the other hand, the globular microstructure showed inferior fracture toughness in terms of crack initation and crack propagation absorbed energy. The lower levels of impact toughness of specimens HP-ed at 950 °C than those HP-ed at the higher temperature were caused by the difference in the total porosity.

TABLE II. Tensile characteristics and toughness of the PM-Ti6Al4V alloy as a function of the hot pressing parameters

Specimen	Types of microstructure[b]	Yield strength MPa	Ultimate tensile strength/MPa	Elongation %	Total absorbed energy (KV 1.5/350)/J	Ai+Ap[c]/J
1	FG	636	693	13	3.5	2.2+1.3
2	CG	643	747	14	4	2.9+1.1
3	G	723	827	18	4.5	2.25+2.25
4	G	741	838	16	6	3.3+2.7
5	CL	746	917	14	7.5	4.7+2.8
6	L	752	920	14	12	8.2+3.8
7	FL	820	923	11	12.5	8.4+4.1
8	FL	835	924	11	15	9.4+5.6

[a]Hot pressing parameters are given in Table I: [b] G = globular, FG = fine globular. CG = course globular. L = lamellar. FL = fine lamellar, CL = coarse lamellar; [c] Ai = crack initiation absorbed energy, Ap = crack propagation absorbed energy

Although the influence of pores crack initiation and propagation cannot be neglected, it is worth noticing that variations in the microstructural morphology are also largely responsible for the differences in the toughness between the various microstructures investigated in this study. The toughness data show that fine lamellar material exhibited a somewhat lower tensile elongation but a much better fracture resistance than material with a coarser microstructure (compare specimens 7 and 8 with 5 and 6, Table II). The inverse dependence of the tensile elongation and impact toughness on colony size and lamellar thickness is a fact that must be considered in explaining these results. This behavior is caused by shear-ligament toughnening and microcrack shielding which cause the finely spaced lamellar material to be more resistant to crack initiation and propagation than the material with the coarser lamellae. Deflection of the main crack by the lamellae, formation of a diffuse zone of microcracks and ligaments ahead of the crack tip and the linkage of the microcracks with the main crack by shear fracture of the near-tip ligaments dominate the fracture process in the lamellar microstructures. The presence of shorter and closer packed α

lamellae contributes to a more frequent change in the direction of crack propagation, providing a high level of energy for the final fracture. Hence, the impact toughness is governed primarily by the lamellar morphology. The results of this study show that refinement of the lamellar microstructure increases the impact toughness by a factor of 2, *i.e.*, the highest total absorbed energy of 15 J was obtained for the specimen HP-ed above T_β for 120 min under a pressure of 60 MPa, whereas the absorbed energy corresponding to the specimen also HP-ed above T_β for 120 min, but only under a pressure of 40 MPa was only 7.5 J. Referring to Table II, a decrease in the lamellar thickness led to an increase in the adsorbed energies required for both crack initiation and propagation. These results also reveal the importance of the morphology on the crack initiation toughness, showing that a higher initiation toughness is connected to a finer lamellar microstructure.

In constrast to globular microstructures, the fully lamellar microstructures demonstrate a crack initiation adsorbed energy about twice that of crack propagation, indicating significantly different fundamental fracture-controlling mechanisms in the two different kinds of process-induced microstructures.[10] As a result, such a fine lamellar microstructures, exhibit considerably higher impact toughness than the globular microstructures. This refined lamellar microstructure possesses the best fracture resistance, by more than a factor of 4 compared to the globular microstructure. To account for the high toughness of this fully lamellar PM Ti6Al4V alloy, not only lamellar refinement, but also lamellae orientation within the colony has to be considered. It is well known that the fracture toughness of specimens with lamellae perpendicular to the direction of crack propagation is much higher than that of specimens with lamellae parallel to the direction of crack propagation.[10]

To verify the observed differences in the fracture behavior, the fracture surfaces of the broken tensile and impact test specimens were examined using SEM. This investigation revealed that both types of microstructure show very similar fracture morphology (Fig. 2).

The ductile mechanism of fracture predominates on the fracture surfaces, although some other modes are also present. The presence of pores, which are crack initiators was more pronounced in specimens HP-ed at the lower temperature, possesing a globular microstructure. As can be seen from Fig. 2a, such pores are rather large and clearly contain a peak spot from which a crack will be initiated. The pores responsible for crack initiation are edged by smooth surfaces, evolving from the brittle fracture. Near the pores, dimpled decohesion regions, representative of a damage that evolved by microvoid growth and coalescence, can be clearly observed. On closer examination of the fracture morphology of the specimen with the fine lamellar microstructure clearly reveals that as the toughness of the specimen increases, ductile fracture prevails and the fracture surface is more dimpled (Fig. 2b). In the case of a globular microstructure however, the fracture mode is less ductile. During crack propagation, a transition from a ductile to a brittle frac-

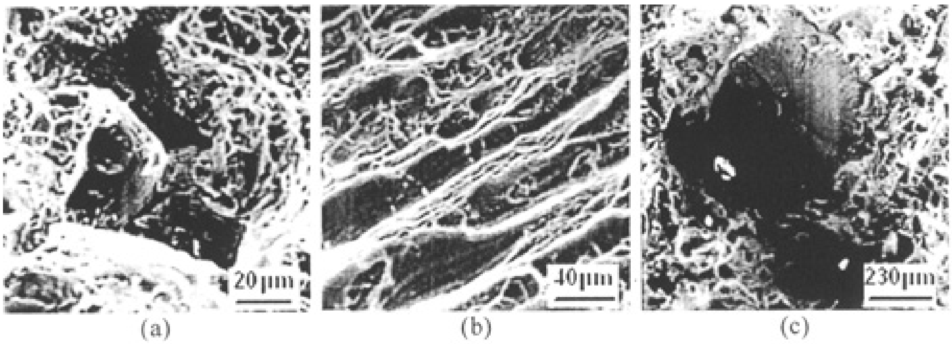

Fig. 2. SEM Micrographs showing the fracture surfaces of the PM-Ti6Al4V alloy after: (a) tensile testing of the specimen hot-pressed at 950 °C and 40 MPa for 60 min, (b) tensile testing of the specimen hot-pressed at 1100 °C and 60 MPa for 120 min and (c) impact testing of the specimen hot-pressed at 1100 °C and 40 MPa for 120 min.

ture, characterized by the presence of cleavages, occurs. A region featuring such a transition is shown in Fig. 2c.

CONCLUSIONS

The effects of the microstructural morphology and residual porosity on the mechanical properties of a Ti6Al4V alloy produced by the PM technique were examined in this study. The main conclusions can be stated as folows.

1. The mechanical properties of a PM Ti6Al4V alloy are very sensitive to its microstructure, which, in turn, varies considerably with changes in the HP-ing parameters.

2. HP-ing this alloy at 950 °C (below the T_{β}) produced a globular microstructure characterized by high open and high total porosity. When the alloy was HP-ed above the β-transition temperature (1100 °C), a fully lamellar microstructure with only some residual porosity was formed.

3. The processing time and pressure have different effects on the characteristics of the lamellar and globular microstructures. Increasing the exposure time and applied pressure coarsened the globular microstructure and greatly reduced its porosity. Variations in these HP-ing parameters had little effect on the residual porosity of the lamellar microstructure, but considerably refined the colony size and thickness of the α lamellae. The processing pressure is the parameter which had the greater influence on this refinement.

4. There is a synergetic effect of the microstructural morphology and residual porosity on the tensile properties and impact toughness.

5. The fully lamellar microstructure was characterized by a high tensile strength, a high impact toughness and a high crack initiation and propagation resistance, while the globular microstructure showed a somewhat better tensile elongation. The finest lamellar microstructure formed during HP-ing for 120 min at 60 MPa displayed the highest impact toughness. Improvement of the impact fracture of the globular microstructure was associated with a decrease in the total porosity level.

6. Both globular and lamellar microstructures show mixed fracture, but the ductile mode is predominant in specimens possessing a fine lamellar microstructure and increased fracture toughness.

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ИЗВОД

УТИЦАЈ МИКРОСТРУКТУРНИХ КАРАКТЕРИСТИКА НА МЕХАНИЧКА СВОЈСТВА Ti6A14V ЛЕГУРЕ ДОБИЈЕНЕ МЕТАЛУРГИЈОМ ПРАХА

ДУШАН БОЖИЋ, ИВАНА ЦВИЈОВИЋ, МИРОЉУБ ВИЛОТИЈЕВИЋ и МИЛАН Т. ЈОВАНОВИЋ

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У раду су приказани резултати испитивања утицаја параметара топлог пресовања на микроструктуру, затезна својства и жилавост Ti6Al4V легуре добијене поступком металургије праха. Резултати испитивања су показали да промене морфологије микроструктуре и заостале порозности компаката значајно утичу на механичке карактеристике легуре. Компактнија ламеларна микроструктура, добијена топлим пресовањем на 1100 ^{o}C, одликује се већом чврстоћом и бољом жилавошћу него глобуларна микроструктура, формирана током топлог пресовања на нижој температури (950 ^{o}C). Иако се код обе микроструктуре јавља мешовити тип лома, дуктилни лом је више изражен код потпуно ламеларне микроструктуре. Контролисањем притиска и времена трајања процеса топлог пресовања може се остварити глобуларна микроструктура смањене порозности, побољшане чврстоће и дуктилности са већом отпорношћу на стварање и раст прслине.

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